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14. ABSTRACT The presented effort is aimed at establishing a framework in order to restore underwater imagery to the best possible level, working w/ both simulated & field measured data. Under this framework the traditional image restoration approach is extended by incorporating underwater optical properties into the system response function, specifically the point spread function in spatial domain and modulation transfer function in frequency domain. Due to the intensity variations involved in underwater sensing, denoising is carefully carried out by wavelet decompositions. This is necessary to explore different effects of restoration constraints, and especially their response to underwater environment where the effects of scattering can be easily treated as either signal or noise. The images are then restored using measured or modeled PSFs. An objective image quality metric, tuned with environmental optical properties is designed to gauge the effectiveness of the restoration, & serves to check the optimization approach. This metric utilized previous wavelet decompositions to constrain the sharpness metric based on grayscale slopes to the edge, weighted by the ratio of the power of high frequency components of the image to the total power of the image. Initial results are presented, including estimation of water optical properties from the imagery-derived MTFs, and optimization outputs applying automated restoration framework.					
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# Automated underwater image restoration and retrieval of related optical properties

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**Abstract**— The presented effort is aimed at establishing a framework in order to restore underwater imagery to the best possible level, working with both simulated and field measured data. Under this framework, the traditional image restoration approach is extended by incorporating underwater optical properties into the system response function, specifically the point spread function (PSF) in spatial domain and modulation transfer function (MTF) in frequency domain. Due to the intensity variations involved in underwater sensing, denoising is carefully carried out by wavelet decompositions. This is necessary to explore different effects of restoration constraints, and especially their response to underwater environment where the effects of scattering can be easily treated as either signal or noise. The images are then restored using measured or modeled PSFs. An objective image quality metric, tuned with environmental optical properties, is designed to gauge the effectiveness of the restoration, and serves to check the optimization approach. This metric utilizes previous wavelet decompositions to constrain the sharpness metric based on grayscale slopes at the edge, weighted by the ratio of the power of high frequency components of the image to the total power of the image. Modeled PSFs, based on Wells' small angle approximations, are compared to those derived from Monte Carlo simulation using measured scattering properties. Initial results are presented, including estimation of water optical properties from the imagery-derived MTFs, and optimization outputs applying automated restoration framework.

**Keywords**— ocean optics; scattering; image restoration; modulation transfer function; point spread function; NIRDD

## I. INTRODUCTION

Due to environmental conditions arising from different water types and associated in-water optical properties, the ability to generally extend the performance range as well as retrieve environmental information from underwater electro-optical system is difficult. This capability however is important for many civilian and military applications, including target detection (e.g. mine detection), search and rescue, and diver visibility[1]. Although traditional image enhancement techniques can still be used for imagery obtained from underwater environments, without knowledge of any processes involved or the optical properties, the effectiveness is considerably restrained. The main challenge working with underwater imagery results from the rapid decay of signals due to absorption, which leads to poor signal to noise returns, and

the blurring caused by strong scattering due to water and its constituents which includes various sized particles. To properly address this issue, knowledge of in-water optical properties and their relationship to the image formation can be exploited in order to restore the imagery to the best possible level. This in turn provides much needed environmental information via through-the-sensor techniques and greatly enhance current operational capabilities.

## II. FRAMEWORK COMPONENTS

### A. Image Restoration

Generally speaking, a 2-dimensional image of an object is basically the combination of original signal,  $f(x,y)$ , convolved by the imaging system response of a point source, the point spread function or PSF  $h(x,y)$ , integrated over sensor space  $\Xi$ :

$$g(x,y) = \iint_{\Xi} f(x_i, y_i) h(x - x_i, y - y_i) dx_i dy_i, (1)$$

The system response includes returns from both the imaging system itself, as well as the effects of the medium.

Mathematically, it is easier to manipulate the above relationship in the frequency domain as the convolution operator becomes a simple multiplication. Applying a Fourier transform, the above relationship becomes

$$G(u,v) = F(u,v)H(u,v), (2)$$

where  $u, v$  are spatial frequencies and  $G, F, H$  are Fourier transforms of  $g, f$  and  $h$  respectively. The Fourier transfer of  $h$ , for example, takes on the following form:

$$H(u,v) = \int \int_{-\infty}^{\infty} h(x,y) e^{-j2\pi(ux+vy)} dx dy, (3)$$

The system response function  $H$ , also referred to as the optical transfer function (OTF), is the Fourier transform of the PSF. The magnitude of the OTF is the modulation transfer function (MTF). The MTF describes the contrast response of a system at different spatial frequencies, and when the phase information is of little concern as is the case for typical incoherent systems, it is a sufficient measure of the power transfer. Notice that the above MTF term  $H(u,v)$  is the total



system response. Therefore if one views the complete path from target to the bottom of eyes or the recording CCD plane, the MTF is the effect of multiple individual components. Because of the cascading nature of the MTF, in the frequency domain, it can be expressed by the direct product of each component, for instance, the optical system itself, and the medium (plus any other factors when applicable):

$$H(u, v) = H_{\text{system}}(u, v)H_{\text{medium}}(u, v). \quad (4)$$

The above formulation, which emphasizes the validity of the separation of the system and the medium, is important in our analysis. Usually the system response  $H_{\text{system}}(u, v)$  can be pre-determined and calibrated to remove any significant errors, and in most cases, does not vary with imaging conditions. Furthermore, one should pay special attention to the band-limiting characteristics imposed by  $H_{\text{system}}$ , such as a camera system's field-of-view, and Nyquist sampling frequency limits imposed by the CCD resolution [2]. From (2), one can see with the knowledge of system MTF  $H(\mu, v)$  and transformed image output  $G(\mu, v)$ , the original image can be theoretically restored by deconvolving the effect in frequency domain to obtain the unblurred version after inverse transform.

Needless to say, the presence of various noises (such as scattering or surface fluctuations) complicates these through-the-sensor techniques. They introduce an extra term in both (1) and (2). The medium effect is two fold: scattering would contribute extra blurring on top of system response, while attenuation results in reduced signal-to-noise ratio. Different image restoration approaches exist to reduce and compensate for the noise to deblur images, such as Wiener, Lucy-Richardson and blind deconvolutions[2]. Under our framework, these approaches are implemented and exploited to determine the best approach working with underwater images. In addition a denoising technique based on the wavelet decomposition is applied[3].

#### B. Modeling of System Response of Underwater Environments

For circular symmetrical response systems, such as the isotropic volume scattering type found in the seawater, the corresponding 2-dimensional transforms found in (3) can be reduced to a one-dimensional Hankel (Fourier-Bessel) integral,

$$H(\psi, r) = 2\pi \int_0^{\theta_{\max}} (2\pi\theta\psi)h(\theta, r)\theta d\theta. \quad (5)$$

Wells [4] applied small angle approximations to the above and derived a robust underwater modulation transfer model which is briefly outlined below. By separating the exponential decay effect with distance due to the medium, the MTF of the medium in (4) can be expressed as

$$H_{\text{medium}}(\psi, r) = e^{-D(\psi)r}, \quad (6)$$

where  $D(\psi)$  is the decay transfer function (DTF) and is independent of the range of detection. This provides a method to compare measurements at different ranges for consistency.

By using a thin slab model with the small angle scattering approximation, and assuming a simple phase function,

$$\beta(\theta) = \frac{b\theta_0}{2\pi(\theta_0^2 + \theta^2)^{3/2}}, \quad (7)$$

Wells [4] showed that the DTF of the seawater can be expressed as

$$D(\psi) = c - \frac{b(1 - e^{-2\pi\theta_0\psi})}{2\pi\theta_0\psi}. \quad (8)$$

$\theta_0$  is related to the mean square angle (MSA),  $b$  is the total scattering coefficient, and  $c$  is the total attenuation coefficient [5]. It has been shown that the exact shape of the scattering phase function does not affect the derived results [6]. With the imaging range defined, the medium MTF can be obtained from (6).

#### C. Image Quality Metric (IQM)

To determine the quality of restored images, besides subjective visual comparison which is prone to significant variations from different viewers, an objective quality metric is needed for these scattering-blurred images. This was critical for the development of an automated restoration scheme, since the computer needs to "know" which direction to "go" and when to stop, on small improvement increments.

Our approach is a wavelet-decomposed and denoised, perceptual metric constrained by a power spectrum ratio. More details can be found in [3]. Briefly, images are first decomposed by a wavelet transform to remove random and some medium noise. This augments chances of true edge detection. Sharpness of each edge is then determined by regression to determine the slope angles between grayscale values of edge pixels versus location. The overall sharpness of the image is the average of measured grayscale angles (GSAs), weighted (WGSA) by the ratio of the power of the decomposition details to the total power of the image. Adaptive determination of edge widths is facilitated by values associated with image noise variances. To further remove the noise contamination, edge widths less than corresponding noise variances or regression requirements are discarded. Without losing generality while easily expandable, only horizontal edge widths are used in this study.

#### D. Framework Summary

The implementation of the framework is termed NRL Image Restoration via Denoised Deconvolution (NIRDD). The flowchart in Fig. 1 shows the process involved in the automated restoration framework. The optimization process is based on the quality of restoration measured in WGSAs. This uses the Wells' model to derive the medium MTF and then the system PSF with knowledge of camera/lens MTF. Both automated and manual input (measured optical properties) can be incorporated in this framework. This framework can be further applied towards real-time image enhancement in the field.



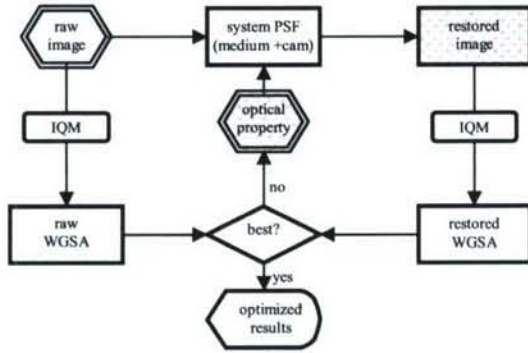


Figure 1. Sketch of the automated restoration framework. Shaded blocks correspond to the storage of optimized data during the process.

### III. INITIAL RESULTS AND DISCUSSIONS

Test image sets were obtained using the Laser Underwater Camera Imaging Enhancer or LUCIE from Defense Research and Development Canada (DRDC), during an April-May 2006 NATO trial experiment in Panama City, Florida. The amount of scattering and absorption were controlled by introducing Maalox and absorption dye respectively. Although the effects of polarizations are examined during the experiment, all images used in this study are unpolarized. In-water optical properties during the experiment were measured. These included the absorption and attenuation coefficients (Wetlabs ac-9), particle size distributions (Sequoia Scientific LISST-100), and volume scattering functions (multi-spectral volume scattering meter or MVSM). Using the framework discussed above, image restoration is carried out and medium optical properties are estimated.

The measured MTFs of lens and LUCIE camera system are used to model the combined system MTF ( $H_{system}(\mu, \nu)$  in (4)), which is shown in Fig. 2, modeled by a Gaussian point response ( $R^2 > 0.99$  in all fits). It is clear that the camera is the limiting factor.

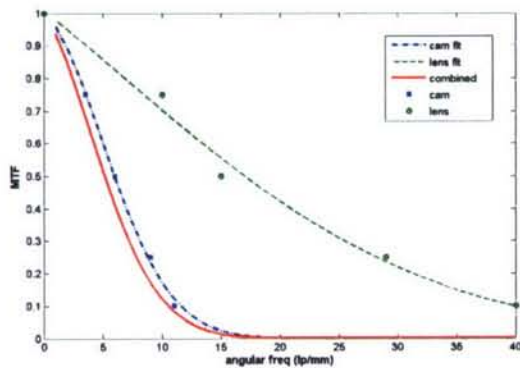


Figure 2. Overall camera system (lens plus camera) MTF. Measured camera and lens MTF were used in Gaussian-type fits.

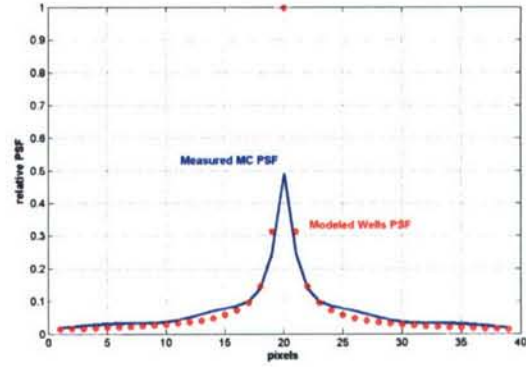


Figure 3. Measured PSF via Monte Carlo (MC) (solid) compared to modeled results (dotted), using data from April 28, 2006 afternoon experiment.

The system response functions (PSFs) of the medium are derived from measurement results of the volume scattering functions and Monte Carlo simulations [7]. Modeled PSFs using (6) are compared to the measurements derived. A comparison of the modeled PSF using (6) and the in-situ measured result is shown in Fig. 3. Note they are in relative units. The discrepancy amongst the two PSFs might be the result of excluding the direct beam contribution in Monte Carlo simulations, which inherently reduces the peak contribution of non-scattered photons. The effect of multiple scattering which is accounted for in Monte Carlo approach also helps to reduce the PSF peak. In either case, they are affected by the sampling frequency limits imposed by detectors in spatial domain.

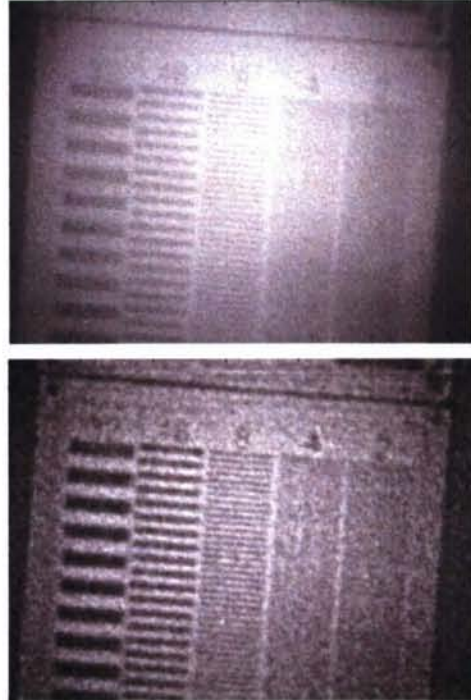


Figure 4. Sample original (top), restored images based on measured PSF and modeled (bottom), with WGSAs values of 0.05 and 0.14 respectively.

The images are restored using PSFs derived from both the modeled and measured optical properties, and then quantified by the image quality metric discussed earlier. A sample pair is shown in Fig. 4, with corresponding WGS values 0.05 and 0.14 respectively. The visual restoration differences between measurement derived PSFs and modeled PSFs are small despite the differences in PSFs (Fig. 3), thus only one is shown. Further details can be found in [3].

An optimization approach is used to estimate underwater optical properties. The forward scattering and the mean square angles are used for initial testing. A set of individual images obtained under different conditions or ranges is used. Via the pathway shown in Table 1, optimization on the image metric is carried out. Table 1 compares the retrieved optical properties with those measured in-situ. While the general trend matches well, significant deviations do exist (eg 0.35 versus 1.0), and is part of ongoing investigations. Possible causes include deficiencies in denoising, the criteria used in the deconvolution algorithms, level of wavelet decompositions, and the edge detection algorithms. Automated batch processing of images obtained within the same time frame should also improve the retrieval.

TABLE 1. ESTIMATED OPTICAL PROPERTIES BY OPTIMIZED IMAGE RESTORATION VERSUS MEASUREMENTS

image ID	range r (m)	measured b (m <sup>-1</sup> )	estimated b (m <sup>-1</sup> )	estimated MSA
25856	5.5	0.56	0.6	0.01
73240	3.9	0.95	0.9	0.02
63402	5.1	0.95	0.7	0.02
72328	7.5	0.35	1.0	0.01

In addition, it is straightforward to obtain medium optical properties from the imagery-derived DTF, by applying the first order Taylor expansion to the exponent for under Wells' formulation (11),

$$\begin{aligned}
 D(\psi \rightarrow 0) &= c - \frac{b(1 - e^{-2\pi\theta_0\psi})}{2\pi\theta_0\psi} \\
 &= c - \frac{b(1 - 1 + 2\pi\theta_0\psi)}{2\pi\theta_0\psi} \\
 &= c - b = a \\
 D(\psi \rightarrow \infty) &= c - \frac{b(1 - 0)}{\infty} = c
 \end{aligned} \quad (9)$$

Taking the following regression equation form following (8)

$$D(X) = C + \frac{A(1 - e^{-X})}{X} \quad (10)$$

results are shown in Fig. 5. The regression parameters for the clearer water are  $A=33.47$  and  $C=0.3989$ . For the turbid setting, they are  $A=44.18$  and  $C=0.7446$ . This approach would yield  $c=0.40 \text{ m}^{-1}$  for the clear water situation, inline with the measurement ( $c=0.35 \text{ m}^{-1}$ ). For the turbid situation, the regression yields  $c=0.74 \text{ m}^{-1}$ , which is smaller compared to the measured value of  $0.95 \text{ m}^{-1}$ . For absorption under the turbid condition, the regression trend is close to the field measured

$a=0.27 \text{ m}^{-1}$ , at low angular frequencies (Fig. 5). Clearly the above result can benefit from measurements at increased spatial frequencies. Higher dynamic ranges will also help eliminate probable digitization errors

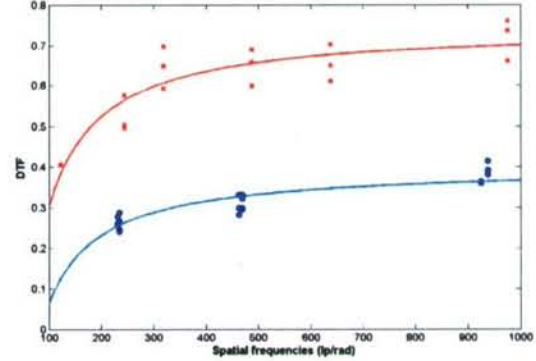


Figure 5. Sample result of retrieved optical properties from measured MTFs based on Wells' small angle scattering theory. Top and bottom curves correspond to turbid ( $c=0.95 \text{ m}^{-1}$ ) and clear ( $c=0.35$ ) conditions respectively.

#### IV. SUMMARY

An automated restoration framework for underwater imagery is implemented, along with through-the-sensor optical properties retrieval. Issues special to underwater imaging such as denoising and image quality assessment are addressed. The model includes the responses of the camera as well as medium. Analytical modeling results compare favorably to Monte Carlo simulations based on measured in-situ optical properties. Lastly initial results presented support the effectiveness of our imaging analysis framework even though further improvements are needed to improve restoration quality and accuracy of optical property retrievals.

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